

PATENT APPLICATION

HOT-SWAP PROTECTION CIRCUIT

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HOT-SWAP PROTECTION CIRCUIT

CROSS-REFERENCES TO RELATED APPLICATIONS

[01] The present application is a continuation application of U.S. Application No.
5 10/029,593, filed December 21, 2001, which is related to and claims priority from U.S.
Provisional Application No. 60/258,004, filed December 22, 2000, both of which are herein
incorporated by reference for all purposes.

BACKGROUND OF THE INVENTION

[02] The present invention relates generally to integrated circuits. More particularly, the
10 invention relates to a method and circuitry for hot-swap protection circuits.

[03] A hot swap operation is an insertion action or a removal action of a device while the
system using it is receiving power, coupling the power from the system to the device. Such
an operation can cause external capacitors to draw currents high enough to disturb system
operations or even cause permanent damage to either or both the device and the system.

15 [04] Hot-swap protection circuits enable electronic circuits to be connected to each other
and disconnected from each other while powered. Hot-swap protection circuits are required
in many applications where it is not practical to shut down an electronic system while
replacing or adding circuit boards to it. Such protection circuits, or systems, are used in
telephone switching hubs, corporate network server hubs, and in laptop or desktop computers
20 with PCMCIA connectors. All of the examples require connection or disconnection under
power and so on.

[05] Conventional hot-swap protection circuits employ connectors with at least one set of
sensor pins, which are a set of extra long and extra short pins, connected to voltage detectors.
These sensor pins allow immediate detection of connection and/or disconnection by sensing
25 the presence and/or absence of the applied voltage. It is well known that a single set of
sensor pins—whether at the top, middle, or bottom—might not be enough to detect a hot-
swap event.

[06] For the best reliability, it is often necessary to use two sets of sensor pins, one set at
the top and one set at the bottom of a hot-swappable card. Adding additional sets of sensor
30 pins increase reliability, but increases costs to the overall system. Additionally, conventional

hot-swap protection systems using sensor pins do not always detect the application or removal of power to a system.

BRIEF SUMMARY OF THE INVENTION

[07] The present invention provides a method and circuitry for hot swap operations.

5 Application of power from a source of power is detected by first circuitry. A switch couples the power to the device in a gradual manner in responsive to the first circuitry. Circuitry is provided which detects an overcurrent condition in which the current draw by the device exceeds a predetermined level. The switch decouples the device from the power responsive to the circuitry. Circuitry is provided detects events in which power is removed momentarily,
10 as occurs in a ground-fault condition, or permanently as in a disconnect event, and in response thereto a signal is produced indicative of the occurrence. Circuitry, which is responsive to noise in the power, is operatively coupled with the switch which varies its conductance in response to the detected noise.

[08] Embodiments of the present invention achieve their purposes and benefits in the
15 context of known circuit and process technology and known techniques in the electronic and process arts. Further understanding, however, of the nature, features, and advantages of the present invention is realized by reference to the latter portions of the specification, accompanying drawings, and appended claims. Other features and advantages of the present invention will become apparent upon consideration of the following detailed description,
20 accompanying drawings, and appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[09] Fig. 1 is a simplified high-level block diagram of an electronic hot-swap protection circuit, according to one embodiment of the present invention;

[10] Fig. 2 is a simplified high-level schematic diagram of the hot-swap protection circuit
25 of Fig. 1, according to one embodiment of the present invention;

[11] Fig. 3 is a simplified high-level schematic diagram of the hot-swap protection circuit of Fig. 1, according to another embodiment of the present invention;

[12] Fig. 4 is a simplified high-level block diagram of an electronic hot-swap protection circuit, according to another embodiment of the present invention;

30 [13] Fig. 5 is a simplified high-level schematic diagram of the hot-swap protection circuit of Fig. 4, according to one embodiment of the present invention;

[14] Fig. 6 is a simplified high-level schematic diagram of the hot-swap protection circuit of Fig. 5, according to another embodiment of the present invention;

[15] Fig. 7 is a simplified high-level schematic diagram of the hot-swap protection circuit of Fig. 4, according to another embodiment of the present invention; and

5 [16] Fig. 8 is a simplified high-level schematic diagram of the hot-swap protection circuit of Fig. 7, according to one embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[17] Fig. 1 is a simplified high-level block diagram of an electronic hot-swap protection circuit 100, according to one embodiment of the present invention. Fig. 1 shows a detector
10 102 coupled in series, via a connector 105, to an electrical power source 107. Detector 102 also couples in series to a fast-disconnect, slow-reconnect switch 110. Switch 110 couples in series along a power supply conductor between a load 112 (circuit to be protected, target circuit, device, etc.) and power source 107. Detector 102 includes an overcurrent detector module 115 and a control circuit 117. Detector module 115 is series-coupled between switch
15 110 and a first terminal of connector 105. Control circuit 117 is coupled to a second terminal of connector 105. Detector module 115 includes an output that feeds into control circuit 117.

[18] In this specific embodiment, detector module 115 and switch 110 couple to the positive terminal of power supply 107, and control circuit 117 couples to the negative terminal of power supply 107. Alternatively, detector module 115 and switch 110 can be
20 located on the negative terminal of power source 107, with appropriate modifications to the circuitry.

[19] In operation, detector 102 detects whether load 112 is hot-swapped in, i.e., reconnected to power source 107. When detector 102 detects a reconnect event, it outputs a hot-swap occurrence indication, or “indication,” or “control signal.” More specifically,
25 detector 102 sends a hot-swap occurrence indication, i.e., a reconnect control signal, to switch 110 instructing it to close, i.e., turn on, in accordance with the invention.

Hot-Swap Occurrence Indication

[20] In this and in other embodiments of the present invention, the hot-swap occurrence indication can serve other functions and will depend on the specific application. For
30 example, the indication can be coupled to drive an LED to notify a user of the hot-swap occurrence. The indication can also be coupled to a controller or microprocessor in the form of an interrupt signal, for example, so that appropriate processing can be performed.

[21] In this specific embodiment, the reconnect control signal is produced by control circuit 117. Also, in this specific embodiment, switch 110 opens quickly but closes slowly. Upon reconnection, the conductivity of switch 110 gradually increases to a fully conductive state, i.e., non-binary change of state that is gradual as opposed to discrete.

5 [22] Upon detection of a reconnect event, detector module 115 produces a signal indicative of a reconnect event. The signal feeds to control circuit 117 which then produces an indication signal and a control signal. The control signal feeds to switch 110. As will be explained below, the control signal is of a nature as to cause switch 110 to gradually increase its conductance (i.e., gradually decrease its resistance).

10 [23] A reconnect event is typified by a detection of a presence of voltage following the absence of current. The term “reconnect” implies the load 112 was previously connected. However, it is possible that a load might never have been connected to the powered system, in which case the term “connect” is more appropriate. For purposes of this disclosure, however, the terms “reconnect” and “connect” are used interchangeably, since both situations
15 are the same from the point of view of a hot swap operation.

[24] Fig. 2 is a simplified high-level schematic diagram of a hot-swap protection circuit 100 in accordance with an illustrative embodiment of the present invention. Hot-swap protection circuit 100 is implemented with commonly available integrated circuits including discrete-active and -passive components (see Figs. 6 and 8, for example). Hot-swap
20 protection circuit 100 includes detector 102 and switch 110, both of which are located on the negative terminal of power source 107. Alternatively, in other embodiments, detector 102 and switch 110 can be located on the positive terminal of power source 107 (as in Fig. 1), with appropriate modifications to the circuitry.

[25] In this specific embodiment, load 112 couples in parallel to a capacitor 120. Fig. 2 shows a schematic of the switch. Typically, the switch 110 is a MOSFET device such as the one shown in Fig. 2 having a part number BUK456. Of course, other commercially available switches can be substituted; e.g., Fig. 6 shows a FET having a part number IRF2807.

[26] Detector module 115 includes an operational amplifier 127, or op-amp 127, configured to output a hot-swap occurrence indication, e.g., a reconnect control signal. The
25 non-inverting input of op-amp 127 couples to switch 110 and inverting input of op-amp 127 couples to the negative terminal of power source 107 via a voltage source 130. A resistor 132 couples between the inverting and non-inverting inputs of op-amp 127. In this specific embodiment, for example, op-amp 127 is implemented with an integrated circuit operational
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amplifier identified by the part number MC33174. Other commercially available op-amps or similar devices can be used.

[27] Control circuit 117 includes a diode 135, resistor 137, and a Zenor diode 140 coupled in series between the positive and negative terminals of power source 107. A resistor 142 and a capacitor 144 couple in parallel between the positive and negative terminals of power source 107. A resistor 147 and a capacitor 150 couple in series with capacitor 144. A transistor 152 couples between a gate switch 110 (node V_{GATE}) and the negative terminal of power source 107. Transistor 152 has a gate coupled to the output of op-amp 217. Node V_{GATE} couples control circuit 117 to switch 110.

[28] In operation, generally, hot-swap protection circuit 100 of Fig. 2 functions to enable the soft (gradual) application of the voltage at node V_{IN} to the load 112. This soft application reduces the stress to the components within load 112 as well as to capacitor 120. Such stress can cause physical damage to these components. For example, if an instantaneous voltage is applied across load 112 or capacitor 120, it is theoretically possible to cause infinite current flow through load 112 or capacitor 120. This can either degrade them or immediately cause them to explode, causing physical damage and possible destruction.

[29] Suppose that after load 112 is reconnected for a sufficient amount of time such that the voltage at node V_{OUT} settles to a voltage close that at node V_{IN} , and a steady state current flow through load 112 is established. The difference between voltages at nodes V_{OUT} and V_{IN} is simply the load current through load 112 times the sum of the resistances of resistor 132 and a resistance R_{dson} of switch 110 in the conducting state.

Operation of Detector 102 upon reconnection

[30] Upon reconnection, hot-swap protection circuit 100 enables a soft turn-on of switch 110 through resistor 147. The soft start sequence is as follows. First, assume that all of the capacitors in control circuit 117, as well as capacitor 120 across the load 112, are discharged so that the potential at node V_{IN} at connector 105 is at zero potential. Second, power source 107 couples to detector module 102 via connector 105. The application of the voltage at node V_{IN} at the output of the connector 105 causes the presence of a voltage E_{IN} , i.e., voltage of power source 107 at node N. Capacitor 144 then charges through resistor 137 to 12V, the voltage of which is determined and limited by Zenor diode 140. In other embodiments, Zenor diode 140 can have other values. During this time, the voltage at node V_{GATE} ramps up from zero potential through resistor 147, implementing a “soft” or slow turn-on of switch 110. The voltage at node V_{OUT} then quickly ramps up from a zero potential to the voltage at

node V_{IN} . The ramp-up rate is determined by the turn-on rate of switch 110 and the size of capacitor 120 across the load 112.

[31] Fig. 3 is a simplified high-level schematic diagram of a hot-swap protection circuit 100 in accordance with another illustrative embodiment of the invention. Hot-swap protection circuit 100 of Fig. 3 is similar to that of Fig. 2. In the embodiment shown in Fig. 3, detector 102 includes circuit 160.

Circuit 160

[32] Circuit 160 includes an operational amplifier 162, or op-amp 162. An output of op-amp 162 couples to the gate of switch 110, or node V_{GATE} , via a resistor 165. Node V_{GATE} couples between resistor 147 and capacitor 150 via a diode 167. A bias voltage source 170 couples in parallel to capacitor 150. In this particular embodiment, bias voltage source 170 is a voltage divider. Bias voltage source 170 includes a resistor 172 and a resistor 175. An inverting input of op-amp 162 couples between resistors 172 and 175 via a resistor 177 and to node V_{GROUND} via a capacitor 180.

[33] In the specific illustrative embodiments of Figs. 2, 3, 5, 6, 7, and 8, V_{GROUND} located at the positive terminal of power source 107 because the protection circuit of these specific embodiments operates in the negative voltage range. The specific voltage range in which the protection circuit operates will depend on the specific application. For example, the operating voltage range can also be in both the negative and positive voltage ranges. In some embodiments, the operating voltage range can only positive voltage ranges, for example, where $V_{GROUND} = 0V$.

Operation of Circuit 160

[34] Circuit 160 protects load 112 from noise that might be present in power source 107. Circuit 160 operates in conjunction with switch 110 to effectively function as a low pass filter of the power from power source 107, thus reducing the effects of noise present in the power. The op-amp 162 is configured as a voltage follower. Noise from power source 107 will propagate through network 170 to the inverted input 13 of op-amp 162 through the network of resistor 177 and capacitor 180. The noise components will cause a differential input to appear at the input of op-amp 162. The resulting output of op-amp 162 will drive switch 110 to alter its conductivity as a function of the noise. This in turn alters the current flow to load 112. Consequently, the power delivered to load 112 will be effectively low-pass filtered by

the switch. Thus, by altering the conductivity of the switch 110 in response to noise present in the power, the noise components in the power delivered to the load 112 can be reduced.

Operation of Overcurrent Detector Module 115 (load connected)

[35] The following description assumes that load 112 has been connected to power source 107 through switch 110, which is on, and through overcurrent detector module 115. As long as the voltage drop across resistor 132 is less than voltage source 130, e.g., $V_{cl}=100\text{mV}$, the output of op-amp 127 will be low, or at the voltage at node V_{IN} . This keeps transistor 152 of control circuit 117 off and node V_{GATE} high which keeps switch 110 on.

[36] An overcurrent condition is one where load 112 demands a much higher than normally expected current. For example, suppose that the current is so high that the voltage drop across resistor 132 is greater than 100mV. This causes the non-inverting input of op-amp 127 to become more positive than its inverting input. Note that the voltage differential across the non-inverting and the inverting inputs occurs when a detected overcurrent condition is detected. In this specific example, an overcurrent is detected when the voltage drop across resistor 132 is greater than 100mV, or if greater than 10 amps of current flow through resistor 132. The threshold current which defines an overcurrent condition can be predetermined by setting voltage level of voltage source 130 accordingly.

[37] Upon detection of an overcurrent condition, overcurrent detector module 115 causes the output of op-amp 127 to go high, or +12V. This turns on transistor 152 to discharge capacitor 150 to the voltage at node V_{IN} . This discharged of capacitor 150, $V_{c1}=\sim 0\text{V}$, causes switch 110 in switch 110 to turn off which results the disconnection of load 112. After switch 110 turns off, the output of op-amp 127 drops back down to 0V, or the voltage at node V_{IN} , because the current through resistor 132 is cut off. Also, capacitor 150 begins to recharge.

[38] The same logical high signal with respect to node V_{IN} (which is available from op-amp 127) becomes an indication output. This indication output indicates an overcurrent fault shut down.

[39] Fig. 4 is a simplified high-level block diagram of an electronic hot-swap protection circuit 100, according to another embodiment of the present invention. Hot-swap protection circuit 100 Fig. 4 is configured similarly to that of Fig. 1 except that circuit 100 of Fig. 4 includes a detector 181 that detects whether load 112 is hot-swapped out, i.e., disconnected from power source 107. In this specific embodiment, detector 102 couples in parallel to a

switch 110. Switch 110 couples in series to a terminal of power source 107 via connector 105 and to load 112.

[40] When detector 102 detects a disconnect event, it outputs a hot-swap occurrence indication, or “indication,” or “control signal.” More specifically, detector 102 sends a hot-swap occurrence indication, i.e., a disconnect control signal, to switch 110 causing it to open, i.e., turn off. Switch 110 opens quickly.

Hot-Swap Occurrence Indication

[41] As stated above, the hot-swap occurrence indication can serve other functions which depend on the specific application. For example, the indication can be coupled to drive an LED to notify a user of the hot-swap occurrence. The indication can also send a signal to a controller or microprocessor as an interrupt signal to perform appropriate processing in the occurrence of a disconnect. During a disconnect event in a storage device, for example, certain cleanup operations can be performed before the drive loses all of its power.

[42] Fig. 5 is a simplified high-level schematic diagram of a hot-swap protection circuit 100, which in some embodiments of the present invention, can be used to implement the hot-swap protection circuit of Fig. 4. Like hot-swap protection circuit 100 of Fig. 4, that of Fig. 5 is implemented with commonly available integrated circuits including discrete-active and -passive components.

[43] Hot-swap protection circuit 100 of Fig. 5 includes detector 181 and switch 110, both of which are located on the negative terminal of power source 107. Alternatively, in other embodiments, detector 181 and switch 110 can be located on the positive polarity conductor of the power source 107 (as in Fig. 4), with appropriate modifications to the circuitry.

[44] In this specific embodiment, detector 181 of Fig. 5 includes the same elements and configuration as that of Fig. 2 with a few exceptions. Detector 181 of Fig. 5 includes a ground-fault protection circuit 185 in place of overcurrent protection circuit 115 of Fig. 2.

[45] Upon detection of a disconnect event, detector module 185 sends an output indication, or “signal,” to control circuit 117. Accordingly, if the signal is triggered by a disconnect event, control circuit 117 sends a disconnect control signal to switch 110 instructing it to open.

[46] Switch 110 couples between the non-inverting input and the inverting input of an op-amp 187 via a voltage source 192.

Operation of Detector 181 upon disconnection

[47] In operation, hot-swap protection circuit 100 of Fig. 5, functions as a load-disconnect protection circuit. Prior to disconnection, assuming that load 112 is powered normally and operational. The voltage at node V_{OUT} is approximately equal to that at node V_{IN} , less the voltage drop across switch 110. The voltage drop across switch 110 is such that the voltage at node V_{OUT} is more positive than that at node V_{IN} , because current is being supplied to load 112 through switch 110 from node V_{IN} . Op-amp 187 of detector 181 connects across switch 110. The non-inverting input of op-amp 187 couples to a voltage source V_{OS} 192. The value of voltage source 192 is approximately -10mV and can vary depending on the specific application. The -10mV ensures that the output of op-amp 187 is low relative to the voltage at node V_{IN} , regardless of the current flow of load 112, or regardless of any finite built-in offset voltages of op-amp 187 (assuming that the input offset voltage of op-amp 187 $< 10\text{mV}$). This keeps transistor 152 off so that node V_{GATE} is charged to 12V , keeping switch 112 on.

Operation of Ground-Fault Protection Circuit 185 (load gets disconnected)

[48] The following description assumes that at some time T1 connector 105 disconnects due to a ground fault-condition. Because there are no capacitors connected between nodes V_{GROUND} and V_{IN} , the voltage at node V_{IN} has the tendency to move towards the voltage at node V_{GROUND} . However, this does not happen because the charge on capacitor 120, which was initially charged to the voltage at node V_{OUT} . Capacitor 120 sustains a current flow from node V_{OUT} to node V_{IN} . As long as there is available charge in capacitor 120 to sustain the current needed by detector 181, it will function properly.

[49] In operation, detector 181 recognizes immediately that the voltage across switch 110 is now reversed, i.e., the voltage at node V_{OUT} is more positive than that at node V_{IN} . The output of op-amp 187 goes high to turn on transistor 152, which in turn discharges capacitor 150. This causes switch 110 in switch 110 to turn off which results the disconnection of load 112. This also stops the discharge of capacitor 120 by the detector 181.

[50] In some embodiments of the invention, because the logical high signal that op-amp 187 outputs also functions as a hot-swap occurrence indication, the indication can be sent to other circuits, e.g., LED, controller, microprocessor, etc., for other purposes.

[51] This circuit technique detects the presence (indication low) or absence (indication high) from detector 181, and represents an automatic ground fault detection without the need for separate ground sense pins as needed in the prior art.

[52] It is to be understood that this specific implementation as depicted and described herein is for illustrative purposes only and should not limit the scope of the claims herein, and that alternative circuit implementations exist for the same functionality. For example, any IC chip, proprietary or otherwise, can be used to implements the circuits described herein.

5 [53] The foregoing circuits can be readily implemented using any of a number of commercially available integrated circuit devices. For example, Fig. 6 illustrates how the hot-swap protection circuit according to the present invention as shown in Fig. 5 can be provided using conventional hot-swap IC devices. Attached as Appendix A is a data sheet for the IC device. Following is a description of the pin outs of the chip:

10 Pin 1 (INV) provides an invert input function. The invert input controls GSNSin's polarity. When invert input is high compared to AGND, then GSNSin low indicates an insertion/removal event. When invert input is low, then GSNSin high indicates an insertion/removal event.

15 Pin 15 (GSNSin) provides a ground sense input. The INV pin controls the polarity sense of this input. A 3uA internal pull-up current source causes logic high when there is no connection at this pin. With INV low or connected to AGND, a GSNSin low (or connected to AGND) will keep RSTout and GATE low, and the external power switch, Q1, off. A disconnected GSNSin pin or when Vcc is applied to it will allow normal operation.

20 Pin 2 (VCCin) is the supply voltage positive power-supply voltage input.

25 Pin 3 (SHNTOff) is the shunt off pin. This pin serves to control the enabling of the shunt circuit. When the pin is high compared to AGND, then the shunt regulator is in off position. A low level at this pin activates the shunt regulator.

30 Pin 4 (CAPin) is an active lowpass filter capacitor input. The output of the power active filter tracks this pin. Adding an external RC network matching the input noise with respect to the 3db point of the filter could reduce the noise to a minimum.

Pin 5 (VDROP) is an active filter offset voltage pin. This pin sets the drop out MOSFET voltage across the active filter.

35 Pin 6 (SLOPE) is a slope input pin. This input controls the current slope during power up and controls inrush currents. Adding external capacitors to this pin allow regulation and adjustment of the rate of the current slope.

40 Pin 7 (OFFTM) is the off-time pin. The OFFTM pin sets the delay time between powerdown and restart of IXHQ100. Delay time can be increased by adding external capacitors to this pin.

Pin 8 (AGND) is the ground pin. This pin provides a system zero reference pin.

45 Pin 9 (VDDout) is the regulator output voltage pin. The regulator output voltage provides current to drive the external circuits with respect to AGND.

Pin 10 (VCL) is the vercurrent threshold bias voltage pin. This pin sets the overcurrent threshold bias voltage.

Pin 11 (SOURCE) is the current input sensor pin. This serves as the input pin for sensing current through the power device with respect to AGND.

Pin 12 (GATE) is the output pin. This is control voltage pin for driving an external MOSFET.

Pin 13 (OUTsns) is the out sensor signal pin. This signal pin senses the output voltage of the circuit.

Pin 14 (RSTout) is the output reset pin. A low at this pin indicates detection of an insert/removal event or overcurrent detection.

Pin 16 (NC) N/A Not Connected

[54] Fig. 7 is a simplified high-level schematic diagram of a hot-swap protection circuit 100, which in some embodiments of the present invention, can be used to implement the hot-swap protection circuit of Fig. 4. Hot-swap protection circuit 100 of Fig. 7 is similar to that of Fig. 5 except that it includes a filter 160. In this particular embodiment, filter 160 is an active filter. Also, filter 160 of this specific embodiment is implemented with commonly available integrated circuits and discrete active and passive components.

[55] Filter 160 of Fig. 7 includes the same elements and is configured similarly to that of Fig. 3 except that the non-inverting input of op-amp 162 couples to the drain of switch 110 as well as to the inverting input of op-amp 187.

[56] Fig. 8 further illustrates how the hot-swap protection circuit according to the present invention as shown in Fig. 5 can be provided using conventional hot-swap IC devices. The circuit shown in Fig. 8 uses the IC device described in the data sheet of Appendix A that can be used to implement the hot-swap protection circuit of Fig. 7. In addition, Figure 1 in the data sheet of Appendix A shows a configuration which implements a hot swap protection circuit according to the present invention as shown in Fig. 3.

[57] Other similar commercially available IC devices can be used to implement the hot swap protection circuits disclosed herein. For example, Linear Technology sells a line of hot swap controllers such as part nos. LT1640AH and LT1640AL. Texas Instruments Incorporated sells a line of hot swap IC devices such as TPS2320 and TPS2321. Maxim Integrated Products sells IC devices such as the MAX5904 which can be used. The disclosed hot swap protection circuitry according to the present invention can be made using such IC devices in conjunction with appropriate external components.

[58] Specific embodiments of the present invention are presented above for purposes of illustration and description. The full description will enable others skilled in the art to best

utilize and practice the invention in various embodiments and with various modifications suited to particular uses. After reading and understanding the present disclosure, many modifications, variations, alternatives, and equivalents will be apparent to a person skilled in the art. The foregoing, therefore, is not intended to be exhaustive or to limit the invention to the specific embodiments described. The claimed invention is intended to be accorded the widest scope consistent with the principles and novel features disclosed herein, and as recited in the following claims.